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RESEARCH ARTICLE

Reliability Based Design of Fluid Power Pitch Systems for Wind Turbines

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ABSTRACT

This paper presents a qualitative design tool for evaluation of the risk for fluid power pitch systems. The design tool is developed with special attention to industry standard failure analysis methods and is aimed at the early phase of system design. Firstly, the concept of Fault Tree Analysis (FTA) is used for systematic description of fault propagation linking failure modes to system effects. The methodology is conducted solely on a circuit diagram and functional behavior. The Failure Mode and Effect Criticality Analysis (FMECA) is subsequently employed to determine the failure mode risk via the Risk Priority Number (RPN). The FMECA is based on past research concerning failure analysis of wind turbine drive trains. Guidelines are given to select the severity, occurrence and detection score that make up the RPN. The usability of the method is shown in a case study of a fluid power pitch system applied to wind turbines. The results show a good agreement to recent field failure data for offshore turbines where the dominating failure modes are valve, accumulator and leakage. The results are further used for making design improvements to lower the overall risk of the pitch system.

KEYWORDS

Reliability, fluid power, pitch system, fault tree analysis, failure mode and effects analysis

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1. INTRODUCTION

Wind turbines play a significant role in the present utilization of renewable energy sources and an increase in investment of new installations is expected [1]. To meet future expectations the Cost of Energy (CoE) produced by wind turbines must decrease. The key factors for decreasing the CoE are low cost, high efficiency and high availability. Since wind turbines are designed to operate as autonomous energy converters, high availability depends on efficient maintenance and high reliability. However in real life, turbines suffer from unpredicted failures causing significant downtime which reduce availability [2, 3, 4, 5, 6]. A number of studies on wind turbine failures have revealed that pitch systems accounts for a substantial amount of total failures and downtime. A European ReliaWind study on app. 350 turbines larger than 1 megawatt, shows that the pitch system contributes over 20% to both the overall turbine failure rate and downtime. This makes it the most unreliable subassembly of the turbine [4]. The study includes wind turbines using either electrical or fluid power pitch systems with unknown distribution. However, indications are that half of the erected variable pitch turbines employ fluid power pitch systems [7]. This paper focuses on the fluid power pitch systems. A recent study by Carroll et al. presents subassembly failure rate for $\sim$ 350 offshore multi megawatt turbines equipped with fluid power pitch systems [6]. These results confirm that pitch systems are the largest contributors to total turbine failure rate. The associated downtime is not directly evident but a similar indicator is found by combining the average repair time and average failure rate. Comparing turbine subsystems by this indicator shows the pitch system faults rank in the top four together with faults related to blades, generators and the gearboxes. A Dutch study on 36 Vestas V90 3 megawatt offshore turbines equipped with fluid power pitch systems show that the pitch system accounts for over 20% of the production stops, only exceeded by the control system [3]. The related total downtime is fourth longest outnumbered only by the gearbox, generator and control system.

From the above studies it is clearly evident that pitch systems contribute significantly to both the downtime and failures of modern multi megawatt turbines. Hence, lowering the failure probability and downtime of such systems will have the potential to significantly increase the availability of wind turbines. To lower the failure probability of pitch systems an important basis is knowledge of failure modes and component failure rates. Two of the mentioned studies addresses the failure modes and failure rates for current fluid power pitch systems. Table 1 shows a list of subjectively determined failure modes identified through the ReliaWind study [4]. Component leakage and sensor faults are seen to be the dominating faults. Failure rate distribution for components and events are seen in Figure 2 obtained from the study by Carroll et al. [6]. Here failure rates related to oil, valves and accumulators faults show to make up a large portion of the total failure rate. The failure rates are categorized from field service reports where information can be inadequate. The *"Others"* category consists of these partially documented failures.

Failure mode 1	**Failure mode 2**	**Failure mode 3**	**Failure mode 4**	**Failure mode 5**
Internal leakage of proportional valve	Internal leakage of solenoid valve	Hydraulic cylinder leakage	Position sensor degraded or no signal	Control valve pressure sensor degraded signal

Figure 1. Important failure modes for fluid power pitch systems. Subjectively identified from the ReliaWind project [4, Fig. 5].

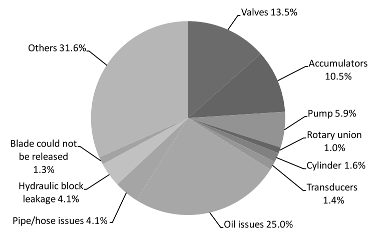


Figure 2. Failure rate distribution for fluid power pitch systems. Reproduced from the study by Carroll et al. [6].

While the failure modes indicate what failures occur and the failure rate indicates how frequent they occur, these studies do not point out why any of the failures occur. Thus the relation between root cause and system failure is unknown. Without knowledge of the root cause and system failure relation, it is difficult to mitigate failures in future pitch system designs.

A state-of-the-art analysis of fluid power pitch systems revealed that only a few sources deal with failure analysis [8]. Failure analysis in this paper is regarded as the qualitative process of analyzing the root cause and effect relation. Yang et al. [9] presented a method for determining reliability based on a Stochastic Petri Net (SPN) of a 500kW Vestas V39 turbine fluid power pitch system. The method mainly concerned the development of an algorithm for determining minimal cut sets of the SPN and not how the SPN is constructed itself. Thus, the failure analysis was not evident and only few failure modes of the system were considered. Han et al. [10] presented a similar approach, where the SPN was defined from a Fault Tree Analysis (FTA). The construction of the FTA was not evident and similarly only considered a sparse number of failure modes for a few of the components. The previous studies on failure analysis of pitch systems have therefore been focused on quantitatively determining reliability and not the root cause and effect relation that underlies the analysis.

Several patents exists describing pitch system concepts with an objective to increase reliability [8]. Many consider redundant components and also closed circuit type systems. However, the actual impact of the designs to reliability remains undocumented.

Within the general field of fluid power, two categories of qualitative failure analysis are seen to be the subject for research [8]. One category of methods uses expert knowledge of component failure modes and automatically determines fault propagation in a system based on a circuit diagram [11, 12, 13, 14]. The other category also uses a circuit diagram, but utilizes component simulation models to determine fault propagation [15, 16, 17]. While some of the methods seem promising for identifying fault propagation, only the work by Stecki et al. [16] and Gjerstad et al. [17] allows for analysing the system risk. Stecki et al. augments an automated fault propagation method with input for a Failure Mode and Effects Analysis (FMEA). However, no additional information is given for conducting the FMEA itself. Gjerstad et al. presents the system risk as a product of reliability and severity of a failure mode [17]. This method is not directly applicable to fault detection on fluid power pitch systems, as the reliability data for fluid power components are very limited. This is also noted by the Gjerstad et al. [17]. In addition, the used risk evaluation method does not cover the influence of condition monitoring.

The reviewed research shows that there still exists a lack of knowledge in the subject of failure analysis of fluid power pitch systems. This gap in knowledge exists in the early design phase and includes constructing the root cause and effect relation, determining how to identify weak spots in the design, and ultimately incorporating this knowledge into more reliable systems.

The main contribution of the paper is to provide a verified design tool that enables systematic analysis of fault propagation and allows for risk evaluation of a fluid power pitch concept in the early design phase of development. This paper also presents design improvements that decrease the overall risk of the fluid power pitch system.

The risk, which is central to the design tool, is determined based on qualitative scores describing severity, occurrence and detectability of failures in the system. The risk score enables identification of weak spots in a concept and directly evaluates the effect of different design changes. To increase usability in industrial development, the design tool incorporates the industry standard failure analysis methods FMEA and Fault Tree Analysis (FTA). Both FMEA and FTA are originally defined in general terms to cover a wide range of mechanical, electrical and software systems [18, 19, 20]. However, this makes the results sensitive to subjectivity and bias issues generally related to qualitative failure analysis. To overcome the subjectivity and bias issues, the design tool focuses on creating a systematic framework that sets both FMEA and FTA in the context of wind turbine and fluid power systems. As its use is aimed at the early design phase of development, the input depends on a circuit diagram and function description.

This paper is arranged as follows. Section two reviews the methods for failure analysis of wind turbine and fluid power systems. Section three describes a generalized fluid power pitch system which is used as a case study to show usability of the design tool. Section four introduces the design tool and uses it on the pitch system. Section five validates the tool by comparing the results with field failure data. Section six presents design changes to the pitch system based on the design tool results and evaluates how risk is affected. Section seven finalizes the paper with conclusions and discussions of the methods and results.

2. FAILURE ANALYSIS

Failure analysis is used for identifying failure mechanisms of a system and to indicate how faults propagate. Failure analysis and reliability modelling are integrated processes, where failure analysis is the qualitative basis for determining quantitative reliability measures [18]. Two methods dominate the area of qualitative failure analysis; Failure Mode and Effects Analysis (FMEA) and Fault Tree Analysis (FTA) [18, 21]. FMEA is a bottom up approach where failure mode(s) of each component is determined with its associated effects (on a higher level) and causes (on a lower level). The analysis is normally documented using tables and enables the analyst to provide details on root cause and failure mode correlation. FMEA is referred to as the general wind turbine failure analysis standard IEC-61400 [22]. The method is therefore generally known and used in the wind turbine industry. A problem associated with FMEA is how to decide which level of detail is necessary for describing the failure characteristics of a system. If the level of detail is too low, not all relevant failure modes will be discovered and thus leaving out potential important weak spots. On the other hand, if the analysis is too detailed, the analysis will become complex and results in high workload [20]. Additionally, it is recognized that by analysing a system bottom up, it can be difficult to overview which effect a component failure mode has to the system. This overview can be achieved using FTA.

FTA considerers the failure propagation in reverse compared to the FMEA. Here, the system is analyzed top down starting from an undesired top event to individual failure modes. FTA is documented graphically using logic gates and provides a systematic approach to connect systems effect to failure mode. The process of FMEA and FTA is summarized in Figure 3. Due to the details provided by the FMEA and the systematic approach of the FTA, many sources advise to use both FTA and FMEA concurrently to detect all relevant failure modes of a system [11, 23, 18]. A major problem related to both FMEA and FTA is that the methods are subjective and exposed to bias from the group of experts performing the analysis [18, 19]. This may compromise the analysis result and will subsequently make it difficult to use as a basis for comparing different design concepts. The design tool to be presented in this paper seeks to lower the bias by introducing specific guidelines for performing the analysis applied to fluid power pitch systems.

Mbari and McCandlish presented a method for constructing an FTA of a fluid power system. The method provides guidance to subdivide the system analysis based on a circuit diagram and knowledge of normal behavior [11]. With adjustments, this method is used as a basis for creating the FTA of the pitch system.

FMEA has been used for comparing two turbine configurations [24]. The study is done based on the Risk Priority Number (RPN), which is a measure calculated for each failure mode of a system. In this case the RPN is a measure of combining both reliability and the risk of not producing electricity. FMEA augmented by the RPN is often named a Failure Mode and Effects Criticality Analysis (FMECA). RPN is normally defined as a product of scores for failure mode severity, occurrence and detection. Based on the MIL-STD-1629A, Arabian et al. [24] defined scales for severity, occurrence, detection and set them in terms of wind turbine taxonomy. The scales are given in Table I.

Severity is directly linked to the system response of a failure mode. The scale for occurrence describes ranges for failure probabilities, but here only the qualitative terms are used for determining the score. This means that the occurrence can be evaluated relatively rather than in absolute values, which makes the rating significantly less complex. Detection is defined as the qualitative probability that a condition monitoring scheme will detect the failure. Guidelines for selecting the scores are given in Section 4. An extension to this FMECA method is made by Tavner et al. [25] to calculate the RPN, not as a

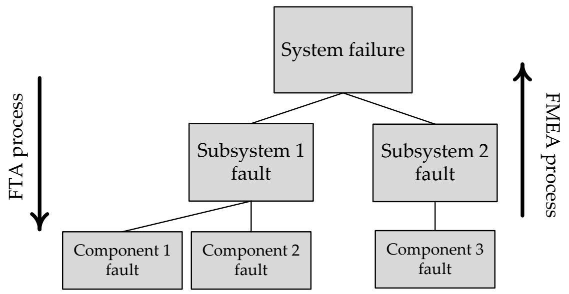


Figure 3. Failure analysis approach using either FMEA or FTA.

Table I. Scales for severity, occurrence and detection reproduced from the work by Arabian et al. [24]

Scale	Description	Criteria
	Severity	
1	Category IV (minor)	Electricity can be generated but urgent repair is required
2	Category III (marginal)	Reduction in ability to generate electricity
3	Category II (critical)	Loss of ability to generate electricity
4	Category I (catastrophic)	Permanent structural damage to the turbine
	Occurrence	
1	Level E (extremely unlikely)	Single failure mode probability of occurrence is less than 0.001
2	Level D (remote)	Single failure mode probability of occurrence is more than 0.001 but less than 0.01
3	Level C (occasional)	Single failure mode probability of occurrence is more than 0.01 but less than 0.10
5	Level A (frequent)	Single failure mode probability greater than 0.10
	Detection	
1	Almost certain	Current monitoring methods almost always will detect the failure
4	High	Good likelihood that current monitoring methods will detect the failure
7	Low	Low likelihood of current monitoring methods to detect the failure
10	Almost impossible	No known monitoring method is available to detect the failure

product of scores, but as given by the following equation:

$$\text{RPN} = 2^{\text{Severity + Occurrence + Detection}}$$

Given the above modified RPN, scores appear as terms in exponents. The benefit is that failure modes with high individual scores are amplified. Also the ratio change in RPN remains the same regardless of the change in individual scores. The modified RPN is used in this paper. To systemize the FMEA procedure Arabian et al. [24] limits both failure modes and root causes. This step is especially helpful when comparing different system designs and is further utilized in the presented design tool.

3. FLUID POWER PITCH SYSTEM

The fluid power pitch system used in this study is shown in Figure 4. The diagram is derived from knowledge of different configurations applied to wind turbines. For clarity, the diagram is divided into three. The supply circuit is located in the stationary nacelle of the turbine and connects to the rotating hub through the main shaft and a rotary union. The rotary union is a component that allows supply and return flow to pass between the rotational movement of the hub to the stationary nacelle. The actuator and safety circuit rotates with the hub and are used for each blade; thus, three are used in total. The actuator circuit consists of two parallel pitch cylinders controlled by a proportional valve. The safety circuit consists of gas accumulators that store pressurized fluid used for actuating the pitch cylinders in the event of an emergency shut down. Emergency shutdown is possible even in the case of a power outage and is achieved by pitching the blades fully to 90° and using them as an aerodynamic brake [22]. The locking circuit is placed parallel to the actuation and safety circuit and enables locking of the blade movement. The pitch system has four modes of operation; start-up, power regulation, emergency shutdown, normal shutdown. An explanation of each is given below.

Start-up is initiated when the turbine is set to begin power production. Here the two pitch cylinders C1 and C2 and the locking cylinder C3 are fully extended and all valves are de-energized. All valves are shown in the de-energized state in Figure 4. All transducers (T1-T7) are checked to be within their specified range. The pump starts and the bypass valve V2 is energized until T2 reads the desired supply pressure. Accumulators A1 and A2 are charged with fluid by energizing valve V5 until T3 reads the desired set pressure. Locking cylinder C3 is then retracted using valve V9 which releases for blade pitch rotation.

Power regulation is active when the turbine is producing power. Pitch cylinders C1 and C2 cause pitch rotation. The cylinders are controlled by proportional valve V6 connected to the supply unit. The pitch system controller receives a pitch angle setpoint depending on the wind speed. The controller sets a voltage signal to valve V6 and adjusts the desired pitch angle equal to the readings of position transducer T4. Valve V5 is de-energized and valve V8 is energized to prevent flow from the accumulators. Valve V7 is energized to allow flow to and from the piston chamber of the cylinders C1-C2. Note that when the cylinders are extended they are driven in the regenerative configuration where rod side fluid is lead to the piston side. Extending the cylinder means pitching out of the wind.

Emergency shutdown is activated by de-energizing all valves and opening for supply fluid from the accumulators to both cylinders. As a result the cylinders extend fully in the regenerative configuration. Note that the safety and actuation circuit is separated by valves V5 and V7.

Normal shutdown is activated when wind speed is too low for power production or the turbine is brought to a scheduled stop. The pitch angle set point is set to fully extend the pitch cylinders and the function is similar to power regulation. When the pitch cylinders are fully extended, the locking cylinder is engaged by using valve V9 connected to the supply circuit. Lastly the supply circuit is de-energized.

The pitch system is considered to fail if the intended function in any of the modes is not achieved. A special case applies for emergency shutdown. This function is safety critical and is normally designed with 2oo3 (Two Out Of Three) redundancy. It is sufficient for two out of the three blades to fully turn out of the wind for performing an emergency stop of the rotor. However, in this event large structural loads are generated due to unbalanced aerodynamic forces. If more than two individual pitch systems fail during the emergency shut down process, the turbine may be exposed to extremely high loads which could result in permanent damage.

4. DEVELOPMENT OF DESIGN TOOL

The design tool takes its basis in combining FTA and FMEA. The flow chart describing the design tool is shown in Figure 5. Firstly, the system is defined using the circuit diagram with all components labeled according to Figure 4. At this point, it is important to select to what extent the analysis should be performed. An adequate level of detail is achieved using the assumptions and prerequisites listed below.

Fault tree developed to failure modes of parts. The Fault tree can be developed to any level of detail of a system ranging from sub-systems, components, parts to physics. The level of detail selected in this analysis reaches the component of the system.

No simultaneous faults. Only single fault events are assumed to occur at any time. The probability of two or more faults occurring simultaneously is regarded as very low in comparison to single fault events for the fluid power system. This assumption greatly reduces the fault tree structure and workload required to perform the analysis.

Initially fault free system. The system is assumed to perform according to design specification at the time it is used. No installation faults, misalignment faults or software faults are considered. This assumption reduces the number of failure modes and root causes. These types of faults may be considered later in the design phase as part of initial system installation considerations.

The failure modes and root causes considered are given in Table II. The failure modes are grouped into five categories which are used in the analysis of the results. Both failure modes and root causes are generated based on experience with fluid power systems and the descriptions found in the work by Totten [21], Watton [26] and Hunt [27].

Mbari and McCandlish [11] suggested to divide fluid power systems into panels. Panels consists of circuits which are not interconnected other than by the supply circuit. For the pitch system, this means dividing actuator and safety circuit from the locking circuit. The fault tree is then constructed panel by panel. During this study, it is found that a more suitable partitioning is done by analyzing the system using operational modes. The operational modes of a system are further referred to only as modes. A mode is defined as a state of operation for a system, it is regarded as either a sequence of operations or a specific function performed by the system. Fully analogue to the description in Section 3, the modes of the fluid power pitch system are start-up, power regulation, emergency shutdown and normal shutdown. The introduction of operational modes greatly reduces the engineering judgment needed to construct the initial part of the fault tree. Not only

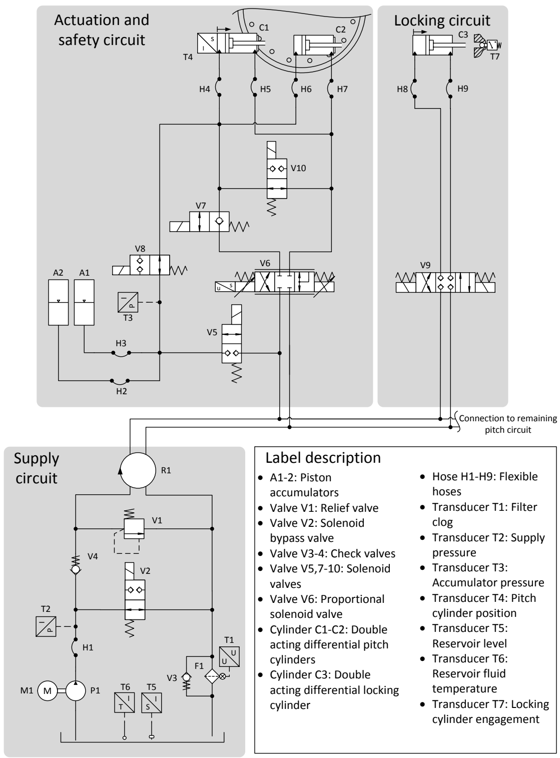


Figure 4. Generalized diagram of a fluid power pitch system. The diagram is based on knowledge from different designs used by the industry. All valves are shown in their de-energized state.

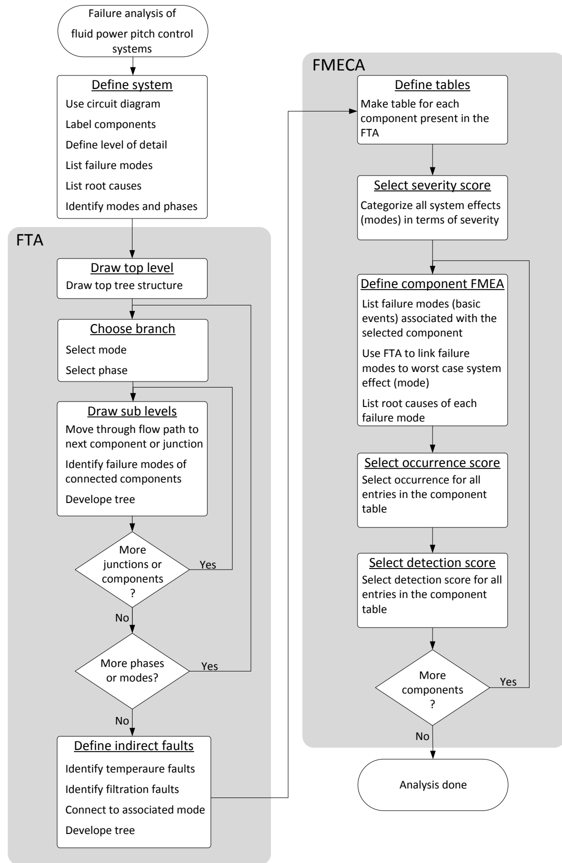


Figure 5. Flow chart describing the proposed design tool used for failure analysis of fluid power pitch systems.

Table II. Failure modes and root causes considered in fluid power pitch systems.

Failure modes

Internal rupture/leakage	External rupture/leakage	Seizure	Electrical faults	Other
Internal fluid rupture	External fluid rupture	Valve seized open	Electrical input malfunction	Blockage
Internal fluid leakage	External fluid leakage	Valve seized closed	Electrical output malfunction	Excessive external load
Internal gas leakage	External gas leakage	Excessive friction	Electrical intermittent malfunction	Structural integrity malfunction
			Electrical signal wire damage	
			Control unstable/malfunction	

Root causes

Fluid borne debris	High pressure rupture	Excessive generated heat	Design error	Electrical overload
Errosion by air in fluid	Pressure cycle fatigue	Solenoid malfunction	Maintenance error	Seal malfunction
Corrosion by water in fluid	Fluid film breach	Spring malfunction	Loss of power	Pressure caused deformation
Errosion/Corrosion by high acid concentration in fluid	High fluid viscosity	Unexpected environmental conditions	Loss of connection	Bearing malfunction

does this introduce a more systematical approach for the failure analysis, it also shows to be necessary for correctly setting the severity score used subsequently in the FMECA.

Next is to identify which components are active and in which state they are set during a particular mode. Many fluid power components are multi-state components, e.g. the proportional valve V6 (see Figure 4). For this valve, three states are permitted: Closed, open (cylinder retracting) and open (cylinder extending). A fault in each state results in different system effects. To analyze all the effects, each mode is subdivided into phases. A phase sets all components in a defined state and allows for identification of the active flow path from supply to reservoir. As an example, consider the upper left part of the fault tree concerning the power regulation mode given in Figure 6. The phases of the power regulation mode are the *"C1 and C2 not extending to setpoint"* phase and the *"C1 and C2 not retracting to setpoint"* phase. Note that these phases are all related to the main objective of the power regulation mode which is to control the pitch cylinder piston to a desired setpoint.

After the system is defined, the top tree structure can be drawn. The top tree level consists of faults in the identified modes and phases. The structure for the pitch system is seen in Figure 6. Note the 2oo3 structure of the emergency shutdown fault where a single pitch system emergency shutdown does not alone result in the top event occurring. The top level also shows filtration faults connected to the multiple emergency shutdown fault event. This is due to the severity of filter burst which is considered in the latter part of this section.

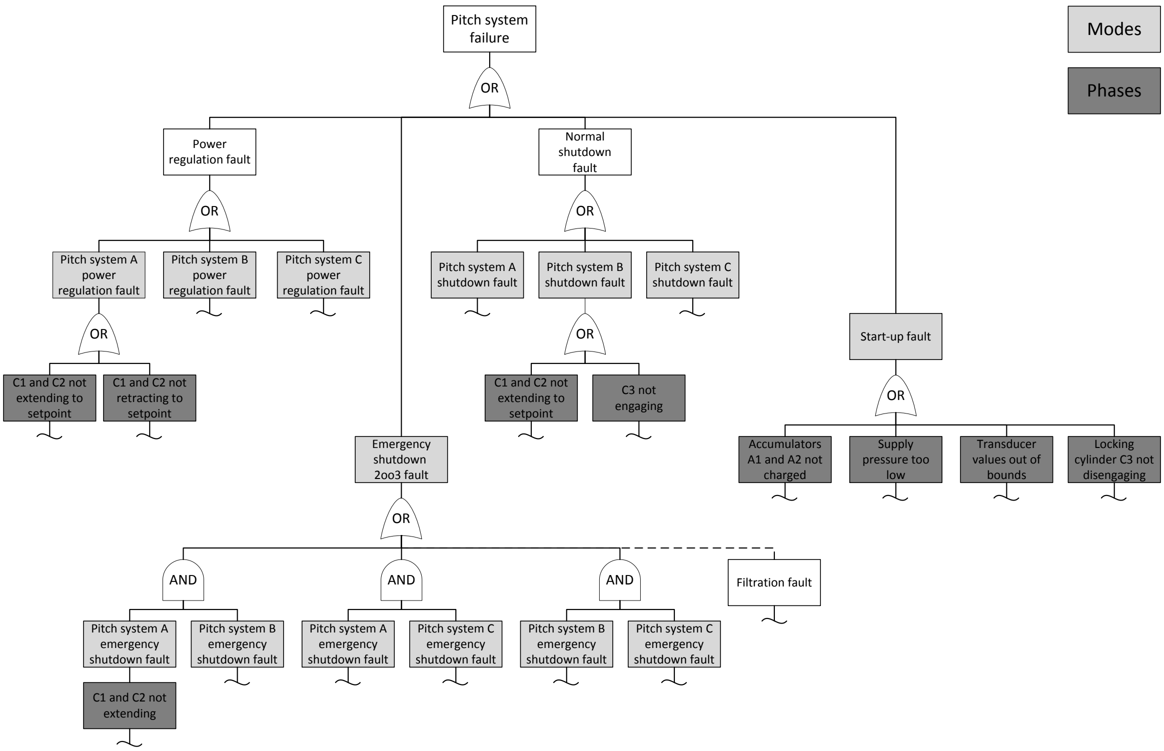


Figure 6. Fault tree top level for fluid power pitch systems.

Next the sub-levels of the fault tree are drawn by selecting a phase and developing it to the failure modes of components connected to the active flow path. These failure modes are bottom events of the fault tree and represented by circles. The procedure is best illustrated by an example considering the *"C1 and C2 not retracting to setpoint"* phase. The fault tree is seen in Figure 7.

The first components considered are the pitch cylinders C1 and C2 and the position transducer T4. The basic events at this level are the failure modes directly related to the cylinder or transducer that result in the cylinders not retracting to the desired setpoint. The failure modes cover excessive external load, excessive friction, structural integrity malfunction and position sensor T4 malfunction. The next level is expanded by categorizing the pressure needed to perform the function as *too high* or *too low*. This approach is similar to the descriptions given by Hogan et al. [13] in the design of an automated failure analysis. It is clear that too low ring port pressure or too high piston port pressure prevents the retracting motion. These two events therefore facilitate the construction of the next level in the tree structure. The ring port chamber is connected to a junction of valve V6, V10, hose H5 and H7. Failure modes that result in either of the components to cause low ring port pressure construct this level. Further analysis is performed by following the active flow path. For the selected phase, this leads to valve V6 and the analysis continue by following the flow path through this component. This procedure is repeated until there are no more active components to follow, which is usually at the reservoir level.

The last step considers filter and temperature fault. The pitch system used in this case study is not equipped with a cooling system, thus temperature fault is not considered. Filtration fault potentially cause the release of a large amount of accumulated fluid borne debris into the system. If the fluid becomes heavily contaminated with debris it is expected that many components become affected and thus violate the no simultaneous faults assumption. Filtration fault is therefore connected to the worst case fault event which is the multiple emergency shutdown fault. This concludes the FTA.

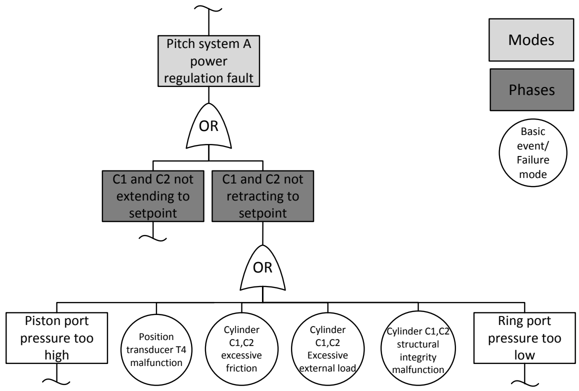


Figure 7. Fault tree example describing faults in power regulation mode.

The FMECA requires tables for all components considered in the FTA. The next step is to categorize all modes in terms of severity. Because many of the part failure modes in the FTA will cause multiple faults, the severity score will aid in selecting the worst case scenario. The categorization is shown in Table III. Note that pitch systems for each blade is named A to C.

Table III. Mode categorization in terms of severity for fluid power pitch systems.

Scale	Description	Mode
1	Category IV (minor)	None
2	Category III (marginal)	Pitch system A-C power regulation fault
3	Category II (critical)	Pitch system A-C emergency shut down fault, Normal shut down fault, Start-up fault
4	Category I (catastrophic)	Emergency shut down 2oo3 fault

The component FMECA is defined by selecting a component and listing all related failure modes (bottom events) from the fault tree. By using the fault tree structure, all failure modes are linked to their corresponding system effects (mode faults). If multiple mode faults are available, the one having the highest severity score must be selected. Lastly, all root causes applicable to the failure modes will be listed.

The final two steps of the failure analysis is to select appropriate occurrence and detection scores. While Table I generally outlines the criteria for selecting the scores, it is up to engineering judgement and experience to apply them in the FMECA. However, some considerations for selecting the scores for fluid power pitch systems is given below.

Occurrence is selected relatively. By assuming proper component design, failure modes caused by high pressure rupture can be considered to be extremely unlikely (score 1). Due to the erratic loads caused by turbulence, a remote probability (score 2) of pressure cycle fatigue is regarded for components connected directly to the pitch cylinders. Pressure cycle fatigue for other components is considered to be extremely unlikely (score 1). Two state solenoid valves (poppet valves) are more robust to leakage and seizure failure modes than proportional spool valves [21]. Therefore leakage and seizure failure modes for the two state solenoid valves are regarded as extremely unlikely (score 1) and occasional (score 3) for spool valves. Fluid borne debris are one of the highest contributors to faults in fluid power systems and is regarded to have a remote probability (score 2) [28].

Detection is related to the condition monitoring methods applied to the system. Faults which can be identified by a fault detection scheme or measured directly by a sensor is regarded as almost certain (score 1). An example is detection of a seized spool in the proportional valve V6 by using the spool position sensor. The rating high (score 4) is given for faults that are measured indirectly. This could, for instance, apply to internal pump leakage causing lowered supply pressure. Low likelihood of detection (score 7) is given to external leakage faults as they are only indirectly measured by the reservoir fluid level transducer. All other failure modes are are considered almost impossible to detect (score 10). It should be noted that faults in fluid power systems that are visible by inspection are also regarded as impossible to detect, because of the long time service intervals for wind turbines.

An overview of the total system RPN distribution is seen in Figure 8. An emergency shutdown fault in a single pitch system is seen to be the largest contributor to system RPN.

Note, while the presented design tool is developed for fluid power pitch systems, it could prove useful for fluid power systems in general. The FTA is not unique to the pitch system and is directly applicable to other fluid power systems.

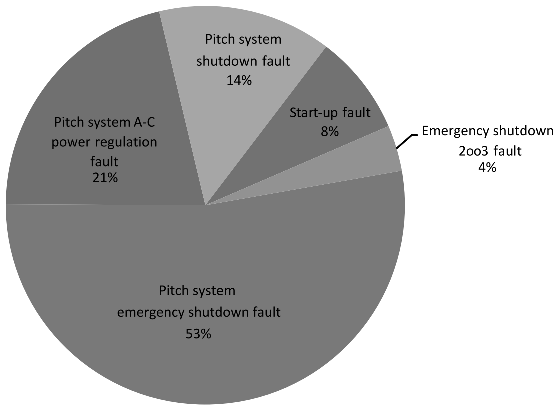


Figure 8. Pitch system RPN distribution.

However, this is not the case for the FMECA, which has to be adapted. Specifically, this could be done by changing criteria for selecting the severity score presented in Table 1. Also the lists of root causes and failure modes in Table II may need to be updated to suit the specific system.

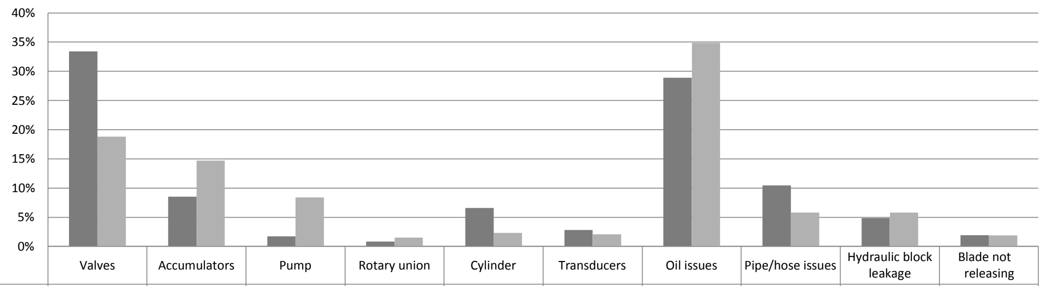
5. VERIFICATION OF DESIGN TOOL

To emphasize the usefulness of the design tool developed in this paper, the results are compared to the quantitative failure data reported by Carroll et al. [6]. Here the field failure data show component and event failure rate of fluid power pitch systems of wind turbines located offshore. They are presented as percentage of the total pitch system failure rate. The reason for only selecting the occurrence score for comparison is that it bears the closest resemblance to the failure rate evident from the field data. The comparison is shown in Figure 9.

The component fault categories cover valves, accumulators, rotary union, cylinders, transducers and pipe/hose issues. To compare occurrence in the component categories, all occurrence scores for the components are simply summarized. The event failure categories are oil issues, blade not releasing and hydraulic block leakage. The oil issues cover unscheduled oil replenishment, oil change and sludge issues. Neither of these failure modes are directly evident from the lists of root causes and failure modes. However, all rupture/leakage failure modes will cause the fluid level to decrease and thus result in needed replenishment. Sludge in the fluid normally causes the filter to clog up and eventually be blocked. Filter failure modes caused by blockage is therefore included under oil issues. Hydraulic block leakage is also not directly evident from the analysis. The hydraulic block is a machined block interfacing to all valves in the actuator, safety and locking circuits. Leakage is assumed to occur in the interfacing parts of the block and valves and occurrence for these faults are summarized and constitute hydraulic block leakage. Lastly, the occurrence for blade not releasing is assumed to be equivalent to occurrence for the cylinder C3 not retracting. Note that *Others*-category has been omitted, and it is assumed that the inadequately documented failures are distributed uniformly to all categories. The field failure rate distribution shown in Figure 9 is therefore generally higher than depicted in Figure 2.

Recalling that the results obtained in this analysis are based on a generalized pitch configuration and qualitative reasoning, the overall tendency is well captured. Categories for valve and oil issues are highest for both field data and results from this analysis. Specifically the field data and analysis result show very good agreement for the categories concerning the rotary union, transducers, hydraulic block leakage and blade not releasing. Here the difference between field data and occurrence is around 1% or lower.

The valves category shows the highest discrepancy between calculated occurrence and field failure rate. The largest single component contributing to valve failure occurrence is the proportional valve V6. If the failure mode occurrence for the proportional valve V6 is lowered to match the failure mode occurrence of the poppet valves, the total occurrence percentage of the valves group is lowered to 31% from original 33.5%. This change decreases the difference between field failure data and occurrence from the analysis. However, the occurrence of valve failure is still overestimated by 11.3% and the change is regarded to have only a little effect on the total occurrence of valve failures. It is likely that the difference in valve failures between the design tool and field data is caused by the coarse occurrence scale, which simply does not cover the failure rate distribution found in the field data. Here failure rates for different failure modes could have a difference that are of order of magnitude apart. Since valves are the most typical component in the pitch system they also constitute



	Valves	Accumulators	Pump	Rotary union	Cylinder	Transducers	Oil issues	Pipe/hose issues	Hydraulic block leakage	Blade not releasing
% of total occurence	33.5%	8.5%	1.7%	0.8%	6.6%	2.8%	28.7%	10.5%	4.8%	1.9%
% of total field failure rate	19.7%	15.4%	8.7%	1.5%	2.3%	2.1%	36.6%	6.0%	6.0%	1.8%

Figure 9. Comparison between calculated occurrence and field failure rate.

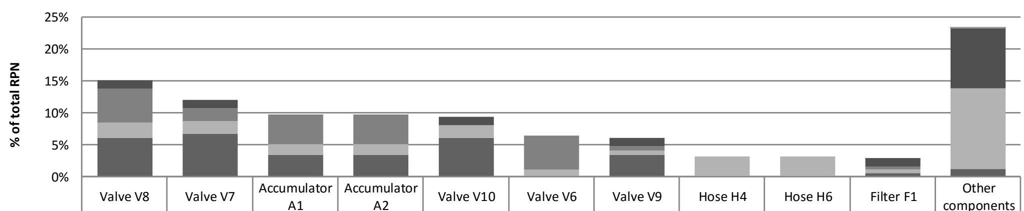
the most occurred failure modes. A large portion of the failure modes for valves receive a score of one, which should have been relatively much lower. The sum of occurrence presented here, is therefore greatly affected by the coarse occurrence scale used.

The relatively large discrepancy for the cylinder category may be caused by the system having two pitch cylinders and the field system only one. This also applies for the accumulators and pump.

In general, Figure 9 shows that a good agreement exists between the field data and the results from the analysis based on the design tool developed here.

6. DESIGN IMPROVEMENTS

The above design tool represents the backbone for investigating design improvements of a pitch system in the early design phase. The design improvements given in this section are based on the component RPN. High component RPN indicates the weak spots of the system in terms of risk. Since the RPN depends on severity, occurrence and detection, a lowered risk implies both an increase in safety and reliability. A pareto chart of the top ten component RPNs is given in Figure 10. Here the components active in the event of emergency shut down (valves V7, V8, V10 and accumulators A1,2), are seen to contribute with high RPN, thus indicating weak spots of the system. High RPN follows the intuition that safety critical components imply high risk. The system RPN is therefore preferably lowered by making design changes that mitigate failure modes for these high risk components. For clarity the failure modes for each component are divided into the categories previously described in Table II.



	Valve V8	Valve V7	Accumulator A1	Accumulator A2	Valve V10	Valve V6	Valve V9	Hose H4	Hose H6	Filter F1	Other components
Other	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.2%
Electrical fault	1.3%	1.3%	0.0%	0.0%	1.3%	0.0%	1.3%	0.0%	0.0%	1.3%	9.4%
Internal rupture/leakage	5.3%	2.0%	4.7%	4.7%	0.0%	5.3%	0.7%	0.0%	0.0%	0.4%	0.1%
External rupture/leakage	2.4%	2.0%	1.7%	1.7%	2.0%	1.0%	0.7%	3.1%	3.1%	0.6%	12.7%
Seizure	6.0%	6.7%	3.3%	3.3%	6.0%	0.0%	3.3%	0.0%	0.0%	0.4%	1.1%

Figure 10. Component RPN Pareto chart with failure mode distribution.

Four risk-based design changes are proposed in the following. The impact to total system RPN is seen in Figure 11.

Parallel redundant valve V8. Valve V8 is the most critical component of the system which is mainly caused by the high seizure RPN. Inspection of the valve V8 failure modes reveals that the valve seized closed failure mode yields the highest RPN. This concurs with the inability to lead fluid from the accumulators to the cylinders in the event of a emergency shut down. Inserting a parallel redundant valve V8 eliminates the valve seized closed failure mode because of the no simultaneous faults assumption. Inserting an additional valve, however, increases the number of leakage paths.

Series redundant valve V7. High RPN is associated with seizure of the valve V7. From the FMECA, it is seen to be caused by the seized open failure mode. Inserting a series redundant valve V7 eliminates this failure mode. Again, the additional valve increases the number of leakage paths in the system.

Spring return locking cylinder C3 and parallel redundant valve V9. Valve V9 implies high risk to the system because of the seized closed failure mode. If the valve is seized closed the locking cylinder C3 cannot be operated. Inserting a parallel redundant valve V9 eliminates this failure mode. Additionally, if the locking cylinder C3 engaging motion is driven by a spring, valve V9 can be replaced by a normally open valve. Valve V9 solenoid and electrical wire malfunction is therefore eliminated. Hose H8 rupture failure mode can also be disregarded.

Accumulators A1,2 piston position transducer. Accumulator risk is associated with seizure, internal and external rupture and leakage failure modes. All have similar system effect and cause the inability to supply sufficient fluid to the pitch cylinders in the event of an emergency shut down. The accumulator piston position is an indicator of either leakage or piston seizure. By introducing accumulator piston position transducers these failure modes can therefore be detected and the associated score can be decreased to the lowest level. The drawback of introducing a piston position transducer is an increased number of electrical failure modes.

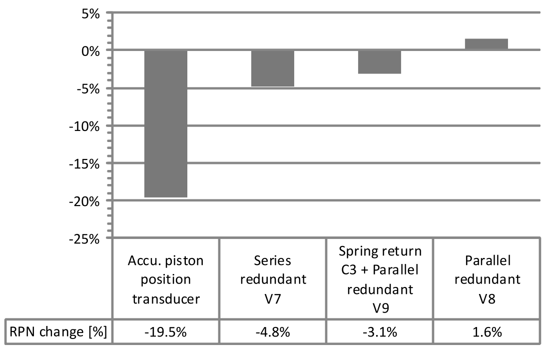


Figure 11. Change in total RPN due to design changes. Lower values are preferred.

From Figure 11 the accumulator piston position transducer is seen to be the most effective design change to lower the system RPN. Also the series redundant V7 and the altered locking circuit decrease the system risk. Parallel redundant V8 valves actually increase the system risk. This is caused by introducing new leakage paths that outweighs the advantages of eliminating the seized closed failure modes. This conclusion underlines why the proposed analysis tool is needed when evaluating design changes. Being able to comparatively evaluate design changes or even different system configurations at the design phase aids in selecting a proper architecture. Also note that the procedure enables for evaluation of system specific condition monitoring methods. Introducing condition monitoring will lower the detection score of the monitored failure mode or component.

Applying all design changes, but the redundant valve V8, to the pitch system results in a significant RPN reduction of 27,4%. The design tool therefore shows the ability to lower system risk. However, the impact of the design changes to failure rate and downtime must first be verified from field tests.

7. CONCLUSIONS

A design tool for risk evaluation was proposed to facilitate qualitative failure analysis of fluid power pitch systems. Based on reliability field studies of multi megawatt wind turbines, it was shown that the pitch system is a large contributor to turbine down time and failure rate. The field data also showed a large number of failures for valves and accumulators. Additionally, leakage faults where seen to be significant. However, the field data did not reveal details of the root causes for failures, and thus, the need for additional failure analysis was established. Past research was shown to focus on quantitative reliability calculation for pitch systems and only few failure modes were previously considered. During the literature review for this work, no past papers were encountered on creating the qualitative basis. This emphasized the need for the design tool. Thus the objective of the paper was to provide industry development with a systematic framework of known methods to aid in selecting proper system architecture in the early design phase.

The presented design tool was based on the industry standard failure analysis methods Fault Tree Analysis (FTA) and Failure Modes and Effects Criticality Analysis (FMECA). FTA was chosen as it enables systematic discovery of relevant failure modes and shows fault propagation through the system. A procedure for performing FTA for fluid power systems was presented, which improves its usefulness when comparing different concepts. FMECA was used to construct a detailed overview of correlation between root cause, failure mode and system effect where the latter two were given by the FTA. The FMECA build upon prior research concerning wind turbine concepts and allowed risk evaluation via the Risk Priority Number (RPN). Guidelines for determining RPN was adapted to pitch systems and standards were established in selecting the severity, occurrence and detection scores.

A case study of a fluid power pitch system applied to wind turbines was conducted to show usability of the design tool developed here. The results showed that valves and accumulators where high contributors to system failure. To verify the design tool a comparison was made between occurrence score and field failure rate. The comparison showed a good agreement between the qualitative results from the design tool and the field data. Design changes were proposed based on the component RPN to lower the overall systems risk. For example, inserting a piston position transducer in the accumulator to monitor leakage showed to significantly lower the system RPN. This design change did not alter the physical layout, but dealt with monitoring of a critical part of the system. The presented design tool therefore allows for risk evaluation of not only physical design changes but also of condition monitoring methods.

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